CLIMATE CHANGE OF MARS: EFFECTS OF OBLIQUITY CHANGES. T. Nakamura and E. Tajika, Department of Earth and Planetary Science, The University of Tokyo (7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; kijun@sys.eps.s.u-tokyo.ac.jp, tajika@eps.s.u-tokyo.ac.jp).

Introduction: Behaviors of the Martian climate system has been investigated in several studies [e.g., 1-4]. If the Martian climate was warm owing to the greenhouse effect of CO_2 in the past, a drastic climate change (climate jump or climate collapse) due to decrease in the amount of CO_2 in the system must have occurred during the evolution from a warm condition to the present cold condition [1, 3]. On the other hand, it is suggested that pulses of CO_2 injected into the atmosphere could place the atmosphere back into a warm state with higher atmospheric pressure [2].

However, these previous studies considered the climate system under the condition of the present obliquity. It is known that the obliquity of Mars could have changed greatly (from 0° to 60°) on short timescales [e.g., 5]. The obliquity change would have profound effects on the climate system of Mars because it alters the latitudinal distribution of the solar radiation. François et al. [6] argued that permanent CO_2 ice caps are stable only under the low obliquity. They proposed that, if the obliquity increases, the atmospheric pressure increases and, therefore, the permanent ice caps become unstable due to enhanced heat transport from the low latitude.

Although it is one of the controlling factors for the stability of the permanent CO_2 ice, other factors may play important roles. For example, when the obliquity becomes large, the solar radiation income onto the pole increases. Also, if the atmospheric pressure increases, the planetary albedo, the greenhouse effect, and the freezing point of CO_2 should change. The energy balance at the pole will depend on all these factors. In this study, we evaluate these effects and discuss the stability of the permanent CO_2 ice more quantitatively from the viewpoint of the energy balance. We also discuss effects of low solar luminosity on behaviors of the Martian climate.

Model: We adopt a time-dependent latitudinally-one-dimensional energy balance climate model for Mars based on the model developed by [4]. We improved the previous model to treat the energy balance of the ground and the atmosphere separately. The model considers the latitudinal temperature distribution, the areal extent of CO_2 ice, and the meridional heat transport. We also consider seasonal changes of the amount of CO_2 ice and the latent heat owing to sublimation and condensation of CO_2. The atmospheric pressure should change owing to changes in the amount of the CO_2 ice. We can obtain a stable periodic solution as a steady state by solving the energy balance and the CO_2 exchange among the atmosphere, the CO_2 ice, and the regolith. The amount of CO_2 adsorbed in the regolith at the steady state is determined from time-averaged atmospheric pressure and surface temperature.

Climate change due to the obliquity changes:
We obtain three kinds of solution of the model: (i) a permanent-ice solution (CO_2 ice throughout the year), (ii) a seasonal-ice solution (CO_2 ice exists only in the winter), and (iii) a no-ice solution. The no-ice solution is obtained when the total amount of CO_2 in the system is larger than 0.5 bar. Estimates of the total amount of CO_2 still have large uncertainties. Furthermore, if the warm and wet climate existed on the early Mars, the total amount of CO_2 should have been larger (an order of 1 bar) than at present and have decreased by some removal processes [3]. We, therefore, considered various cases for the amount of total CO_2 in this study.

Based on behaviors of the Martian climate system, it is essential for the solutions to be classified into the following two regime [4]: (I) ``permanent-ice regime'' and (II) ``no-permanent-ice regime'' (referred them in [4] as residual-cap regime and no-residual-cap regime, respectively). The permanent-ice solution belongs to the permanent-ice regime, and both the seasonal-ice solution and the no-ice solution belong to the no-permanent-ice regime.

Climate jumps between these two climate regimes will occur due to the obliquity changes. For example, the no-permanent-ice regime with 0.3 bar of the total CO_2 can not exist when the obliquity is lower than 12.5°. This is because, when the obliquity is small, the solar radiation income onto the pole becomes too small to sublimate the seasonal CO_2 ice completely in the summer. Considering the no-permanent-ice regime on a decreasing phase of the obliquity, the climate system will jump from the no-permanent-ice regime into the permanent-ice regime by runaway condensation of CO_2, when the obliquity decreases to <12.5°.

On the other hand, the permanent-ice regime disappears when the obliquity is higher than 31.75°. Therefore, another climate jump from the permanent-ice regime to the no-permanent-ice regime will occur by runaway sublimation of the permanent CO_2 ice when the obliquity increases to >31.75°. In order to understand the reason for the climate jump from the permanent-ice regime quantitatively, we examine an energy balance at the pole. The annually net latent heat must be zero when the CO_2 budget is in an equilibrium. If the obliquity becomes larger than a certain value, the energy income onto the pole always exceeds the outgoing radiation from the permanent CO_2 ice. This means that the energy balance is not obtained and thus the permanent CO_2 ice cannot exist any more. Therefore, runaway sublimation of CO_2 ice should occur, and the climate state will change to the no-permanent-ice regime.

Climate jumps between the two climate regimes and, therefore, hystereses of climate change should be the most remarkable effects of the obliquity change on the Martian climate system.

Results for the reduced solar luminosity:

According to stellar evolution models, the solar luminosity has increased with time [e.g., 7]. When Mars was formed, the solar luminosity was probably 30-25% less than its current value. Because the energy balance depends largely on the solar luminosity, it is necessary to take into account the evolution of the sun in order to consider the evolution of the Martian climate system.

In the low-luminosity case, there is a remarkable difference in behavior of the permanent-ice regime: it exists even in the higher obliquity region for the 70% luminosity case. Latitudinal distribution of the solar radiation plays a key role in this feature. If the obliquity is more than ~50°, the solar radiation onto the mid-latitude region is the lowest. The remarkable change in the distribution of the solar radiation has an important influence on the energy balance. Consequently, there is a solution of the energy balance on the permanent CO_2 ice at the pole, even if the obliquity is as high as 50°. When the obliquity is 60°, the mid-latitude energy income is the lowest and, therefore, the permanent CO_2 ice forms circularly in the mid-latitude region (Figure 1). This might be because it is the region of the lowest solar radiation and the ice can survive against sublimation in the summer. The permanent CO_2 ice in the mid-latitude should be called an ``ice ring" rather than an ``ice cap". Figure 1 shows a typical solution which has ice rings in both hemispheres (although an ice ring in one hemisphere may be obtained, depending on the initial distribution of CO_2 ice).

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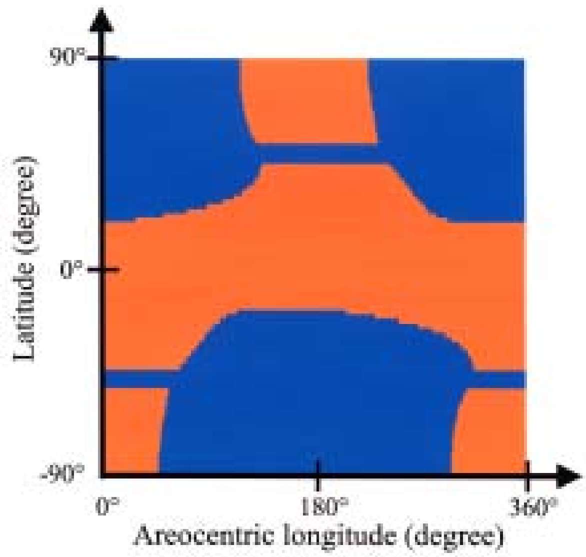

Figure 1. Seasonal distribution of the CO_2 ice under the condition of the 70% luminosity and 60 of the obliquity. Blue regions represent existence of the CO_2 ice, and red regions represent an uncovered surface. Residual CO2 ice forms a ``ring".